EPJ manuscript No.
(will be inserted by the editor)

Fermilab FERMILAB-CONF-05-496-E CDF AND D0

Searches for BSM (non-SUSY) physics at the Tevatron

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Received: date / Revised version: date

Abstract. As of July 2005, the Tevatron at Fermilab has delivered ≈ 1 fb^{-1} of data to the CDF and DØ experiments. Each experiment has recorded more than 80% of the delivered luminosity. Results of searches for physics (non-SUSY and non-Higgs) beyond the Standard Model using 200 pb^{-1} to 480 pb^{-1} at DØ and CDF are presented.

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1 Introduction

The discovery of anomalous behavior in data collected at high energy physics experiments could provide non-SUSY and non-Higgs explanations to questions associated with the Standard Model and provide deeper understanding to the fundamental particles and interactions in nature. Such questions include whether quarks and leptons are composite particles, the existence of extra dimensions, and the answer to the hierarchy problem in the Standard Model (SM).

Generally, a search is approached by first understanding the SM prediction for a given signal and detector backgrounds which could mimic that signal. Analyses are optimised for signal, not according to model, prior to looking in the signal region of the data. If no anomalous behavior is found, the signal acceptances of various models can be used to set limits.

Searches for Z', Lepton-Quark compositeness, Randall-Sundrum Gravitons, Large Extra Dimensions, W', Leptoquarks and Excited Electrons are presented here.

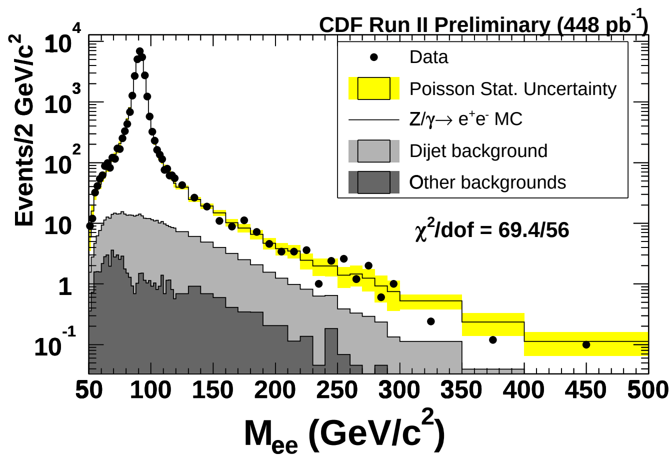

Fig. 1. Expected and observed dielectron mass distributions.

2 High Mass Dilepton Searches

High mass dilepton searches are experimentally motivated by the small source of background, with the exception of the well-understood, irreducible Standard Model Z/γ^* production. Search results can be used to study many theories: extended gauge theories (Z'), technicolor, lepton-quark compositeness, large extra dimensions (LED), and Randall-Sundrum gravitons.

2.1 Z'

The majority of extensions to the SM predict new gauge interactions, many of which naturally result in the prediction of neutral or singly charged bosons, such as a highly massive "Z'" particle.

2.1.1 Z' Searches using M_{ee} and $\cos\theta^*$

Using 448 pb^{-1} of data, CDF searched for Z' production by studying the distributions dielectron mass at high mass and the angular distribution $\cos\theta^*$ in the Collins-Soper frame[4]. Figures 1 and 2 show the M_{ee} and $\cos\theta^*$ distributions, respectively.

Having observed no evidence of a signal, limits at the 95% confidence level (C.L.) are set for the sequential Z'[1] and E6 Z' models[2], as shown in Table 1. With 448 pb^{-1}, using the $\cos\theta^*$ information effectively increases the amount of data by $\approx 25\%$ for the sequential Z' model.

Additionally, a general formalism for Z' which uses M_{ee} and $\cos\theta^*$[3] and allows for new models to be easily checked is studied. The formalism consists of four general

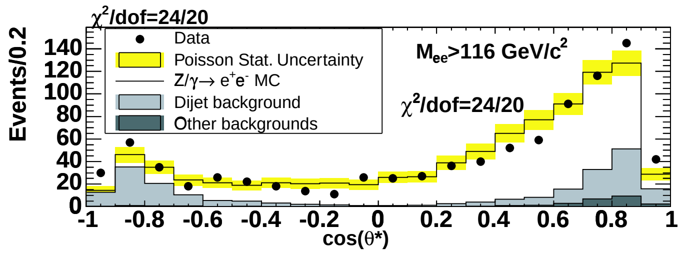

Fig. 2. Expected and observed $\cos\theta^*$ distribution for $M_{ee} >$ 116 GeV/c^2.

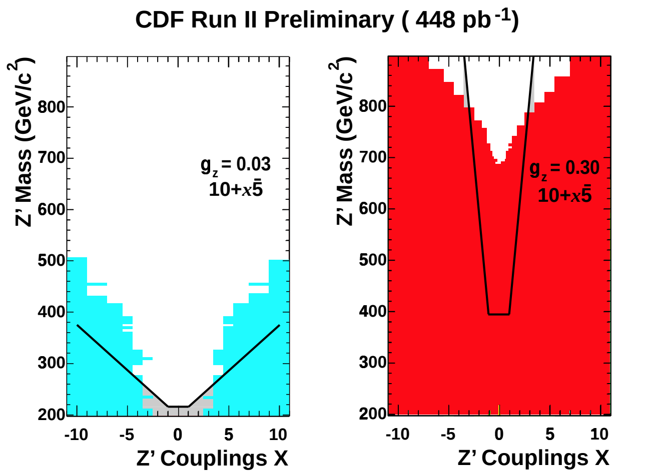

Fig. 3. Exclusion regions using a generalized formalism for Z' searches.

model classes and are each defined by three parameters: mass ($M_{Z'}$), strength ($g_{Z'}$) and coupling parameter (x). Figure 3 shows the CDF exclusion regions for one of the model classes for two values of $g_{Z'}$. The area below the black curves represent LEP II [3] exclusion regions obtained via indirect searches for contact interactions.

2.1.2 Traditional Z' Searches

CDF and DØ both performed "traditional" Z' searches which focus on the dilepton mass distributions. All three channels - electron, muon, and tau - were studied with no evidence for a signal beyond the Standard Model expectations. Table 1 shows a summary of the limits set at the 95% C.L. for various Z' models.

2.2 Quark-Lepton Compositeness

Contact Interaction composite models introduce hypothetical constituents of quarks and leptons called "preons" which are bound together by a characteristis energy scale known as the compositeness scale (Λ)[5]. The differential cross-section can be written as in Equation 1.

$$\frac{d\sigma_T}{dM} = \frac{d\sigma_{SM}}{dM} + \frac{I}{\Lambda^2} + \frac{C}{\Lambda^4} \quad (1)$$

Table 1. Limits from CDF and DØ on the sequential Z' and E6 models using the charged lepton channels. Units on the limits are in GeV/c^2.

Sequential Z'	ee	$\mu\mu$	$ee+\mu\mu$	$\tau\tau$	Luminosity (pb^{-1})
CDF	750	735	815	394	200
CDF with $\cos\theta$	845				448
DØ	780	680			200-250

E6	Z_l	Z_X	Z_Ψ	Z_η	Channel
CDF	615	675	690	720	$ee+\mu\mu$
CDF with $\cos\theta$	625	720	690	715	ee
DØ	575	640	650	680	ee

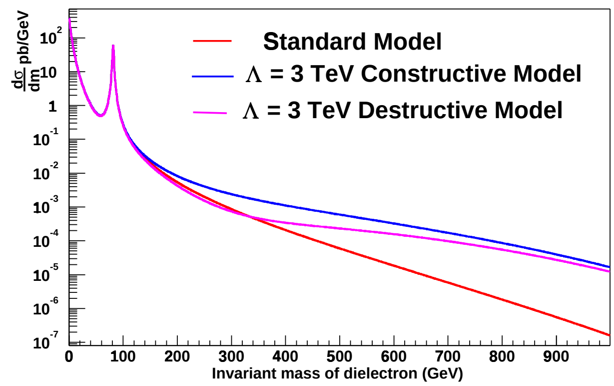

Fig. 4. M_{ee} distributions for SM dielectron production and for constructive and destructive interference due to contact interactions.

For energies accessible at the Tevatron, the intference term (the second term) dominates and quark-lepton compositeness would be discovered as an excess in the tail of the dilepton distributions, an example of which is shown in Figure 4.

No evidence for signal is found in a dielectron search of 271 pb^{-1} or in a dimuon search of 400 pb^{-1} at DØ. The dimuon results are shown in Figure 5. Limits are set on Λ for several models as shown in Table 2.

2.3 Extra Dimensions

2.3.1 Large Extra Dimensions

Large Extra Dimensions (LED) provide a non-SUSY alternative to the "hierarchy" problem in the SM and an explaination for the large difference between the electroweak and apparent Planck scales ($M_{EW} << M_{Pl}$). The signature for LED is dilepton or diphoton production. The Large ED (ADD) model[6] predicts an increase in cross-section at high mass and depends on parameter $\eta_G = F/M_s^4$ where F is a model dependent dimensionless parameter and M_s is the UV cutoff, $M_s \sim M_{Pl(4+n\ dim)}$, also termed the fundamental Planck scale. An example $M_{ee} + M_{\gamma\gamma}$ distribution for $\eta_G = 0.6$ is shown in Figure 6

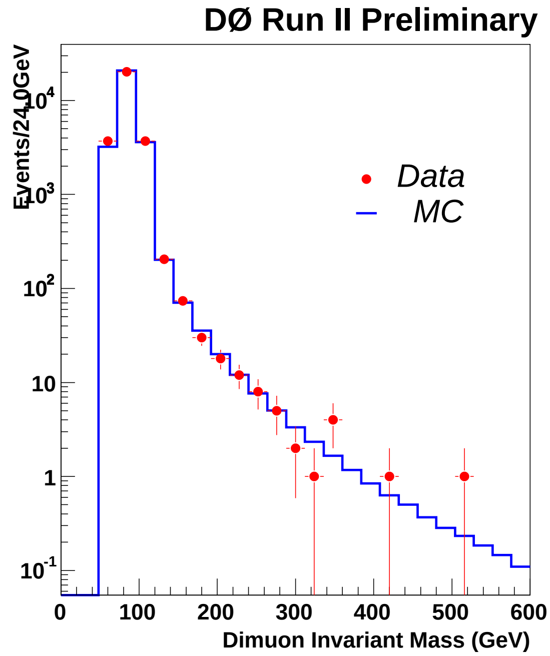

Fig. 5. $M_{\mu\mu}$ distribution using 400 pb^{-1}.

Table 2. Limits from DØ on the compositeness scale for several models using 271 pb^{-1} of dielectron data and 400 pb^{-1} of dimuon data.

Model	$\Lambda-$ ee	(TeV) $\mu\mu$	$\Lambda+$ ee	(TeV) $\mu\mu$
LL	6.2	6.9	3.6	4.2
RR	5.8	6.7	3.8	4.2
LR	4.8	5.1	4.5	5.3
RL	5.0	5.2	4.3	5.3
LL+RR	7.9	9.0	4.1	5.0
LR+RL	6.0	6.1	5.0	6.4
LL-LR	6.4	7.7	4.8	4.9
RL-RR	4.7	7.4	6.8	5.1
VV	9.1	9.8	4.9	6.9
AA	7.8	5.5	5.7	5.5

along with the background prediction and observed data for 200 pb^{-1} of dielectron and diphoton data at DØ. Figure 7 shows no anomaly in the ee, $\gamma\gamma$ $\cos\theta^*$ distribution. By fitting M_{ee}, $M\gamma\gamma$, and $\cos\theta^*$, DØ extracts limits on η_G at the 95% C.L., from which lower limits on the fundamental Planck scale are set. In the GRW[6] formalism, $F = 1$ and the Run II limit is $M_s > 1.36$ TeV. The combined Run I + Run II DØ limit is $M_s > 1.43$ TeV.

2.3.2 Warped Extra Dimensions

The Warped Extra Dimension model predicts one extra dimension that is highly curved and the production of Randall-Sundrum (RS) gravitons[7]. The model depends on k/M_{Pl}, where k is the curvature scale. CDF and DØ search for RS gravitons by studying the M_{ee}, $M_{\mu\mu}$, and

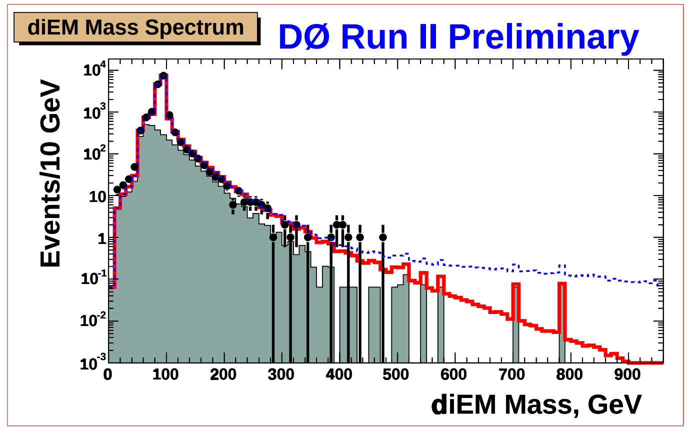

Fig. 6. Background prediction and observation of M_{ee}, $M_{\gamma\gamma}$ distributions. The dotted blue spectrum shows the LED theoretical prediction for $\eta_G = 0.6$.

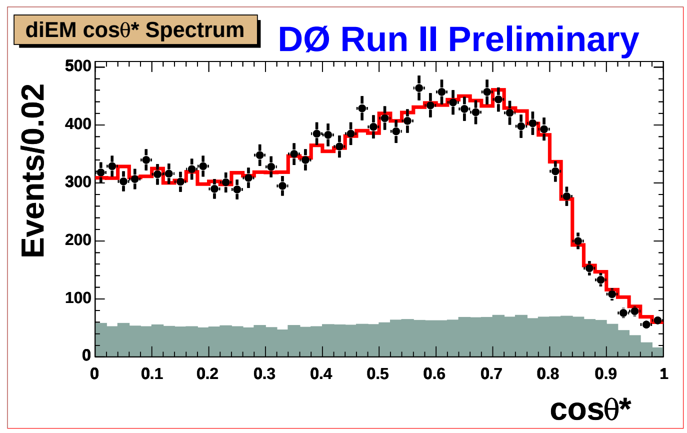

Fig. 7. $\cos\theta^*$ predicted and observed distributions for ee and $\gamma\gamma$ ($\cos\theta^*$ is different than that discussed in 2.1.1).

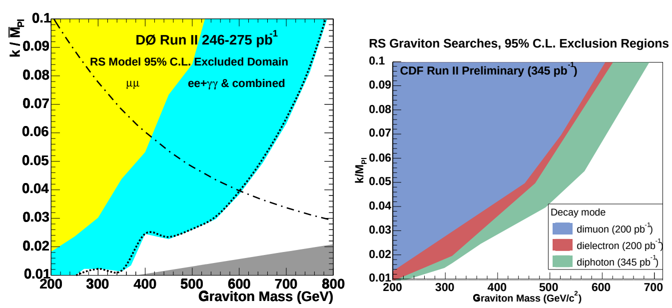

Fig. 8. Limits set on Randal Sundrum Graviton production at DØ and CDF.

$M_{\gamma\gamma}$ distributions for a resonance which would depend on k/M_{Pl}. Two-dimensional exclusion regions in the $k/M_{Pl} - M_G$ plane are established as shown in Figure 8.

3 Charged Heavy Vector Boson (W')

The production of charged heavy vector bosons, referred to as W' particles, are predicted in theories based on the extension of the gauge group[8]. The W' is modeled to

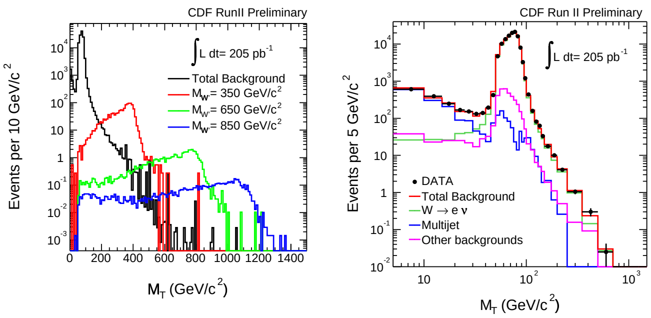

Fig. 9. The left plot has transverse mass distributions of the expected background overlaid with three W' mass choices. The right plot shows the transverse mass distributions of the irreducible SM $W \to e\nu$, multijet, and total background sources. The data is plotted and agrees well with the expectation.

decay to an electron and neutrino, where the neutrino is assumed to be SM-like: light and stable. Thus, the final state signature in the detector is a high p_T electron with high missing E_T. CDF performs a direct search for W' production and Figure 9 shows the background due to SM $W \to e\nu$ production with the predicted transverse mass distributions for W' production at three different W' masses.

Figure 9 shows the expected background distributions and the observations in the data. No $e\nu$ signal above the SM expectation is observed. However, the agreement between the data and the background prediction indicate good understanding of the calorimeter energy at CDF and the detector missing energy.

Having observed no signal above the SM expectation, the limit at the 95% C.L. is set on W' production using a binned likelihood fitting method. The CDF Run II search excludes W' masses less than 842 GeV/c^2. The CDF Run I limit was $M_{W'_{SM}} > 754$ GeV/c^2.

4 Leptoquarks

Many extensions of the SM assume additional symmetry between lepton and quarks which requires the presence of a "new" particle, a leptoquark (LQ)[9]. Leptoquarks, which could be scalar or vector particles, carry both lepton and baryon numbers. They are assumed to couple to quarks and leptons of the same generation; thus, there are three generation of leptoquarks for which one could search.

Leptoquarks would be pair produced at the Tevatron. Their decay is controlled by parameter β, where $\beta = B.R.(LQ \to lq)$. There are three final state signatures for LQ pair production at the tevatron: two charged leptons and two jets ($lljj$); one charged, one neutral lepton and two jets ($l\nu jj$); and two neutral leptons and two jets ($\nu\nu jj$). The experimental signal is a resonance in the lepton-jet invariant mass spectrum.

No evidence of LQ production is found at DØ or CDF. Figure 10 shows the two dimensional exclusion region established by DØ for the first generation with $eejj$ and $e\nu jj$

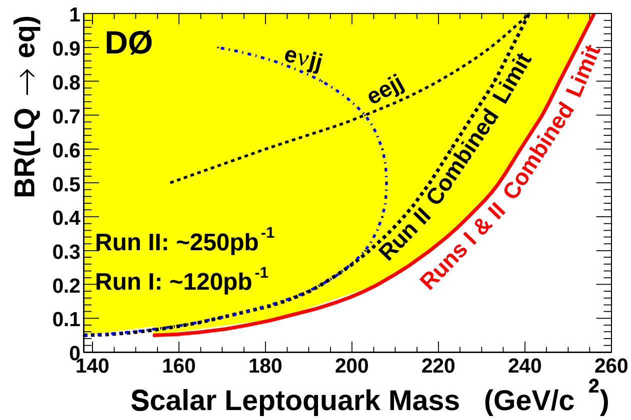

Fig. 10. Exclusion region established by DØ for first generation leptoquarks.

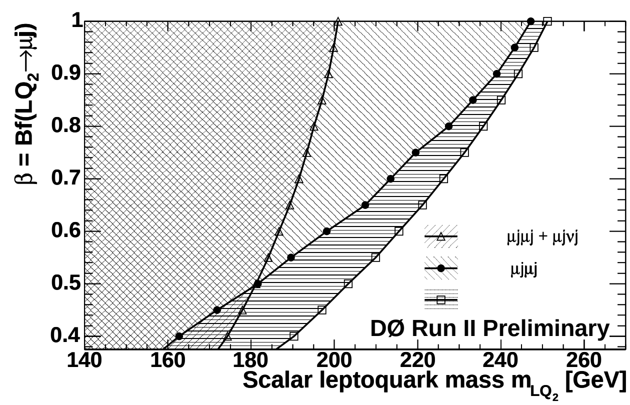

Fig. 11. Exclusion region established by DØ for second generation leptoquarks.

final state signature. DØ combines 250 pb^{-1} from Run II with 120 pb^{-1} of data from Run I to obtain the exclusion region shown in Figure 10. For the case of $\beta = 1$, DØ excludes first-generation leptoquarks with masses less than 256 GeV/c^2. CDF excludes masses less than 235 GeV/c^2 using 200 pb^{-1} from Run II.

Figure 11 shows the exclusion regions for generation two leptoquarks from DØ. DØ searches for $\mu\mu jj$ and $\mu\nu jj$ production; CDF searches for $\mu\mu jj$, $\mu\nu jj$, and $\nu\nu jj$ production. For $\beta = 1$, DØ Run I + II excludes LQ masses less than 251 GeV/c^2 while CDF Run II excludes mass less than 224 GeV/c^2.

CDF has performed a search for third generation LQ production using the $\tau\tau bb$ signature. Leptoquark masses less than 129 GeV/c^2 are excluded for $\beta = 1$ using 200 pb^{-1} of data.

5 Excited Electrons

The observation of excited states of leptons or quarks would be a first indication that they are composite particles. CDF searches for singly produced excited electrons

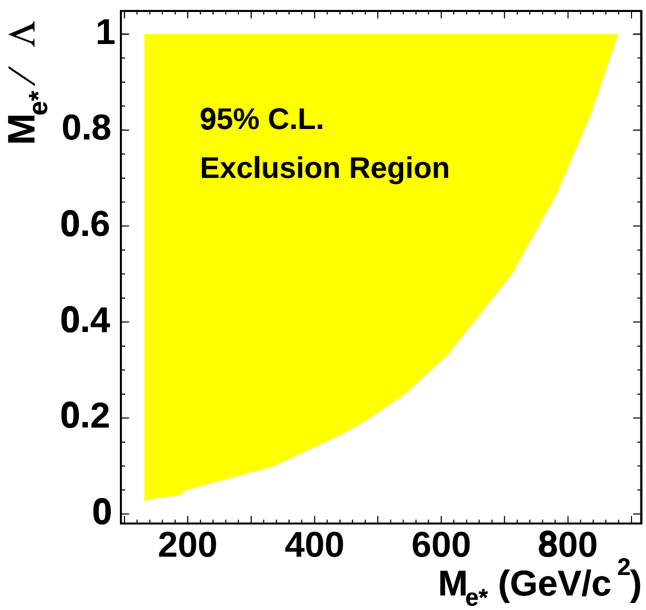

Fig. 12. Exclusion region at the 95% C.L. established by CDF for e^* production via a Contact Interaction model.

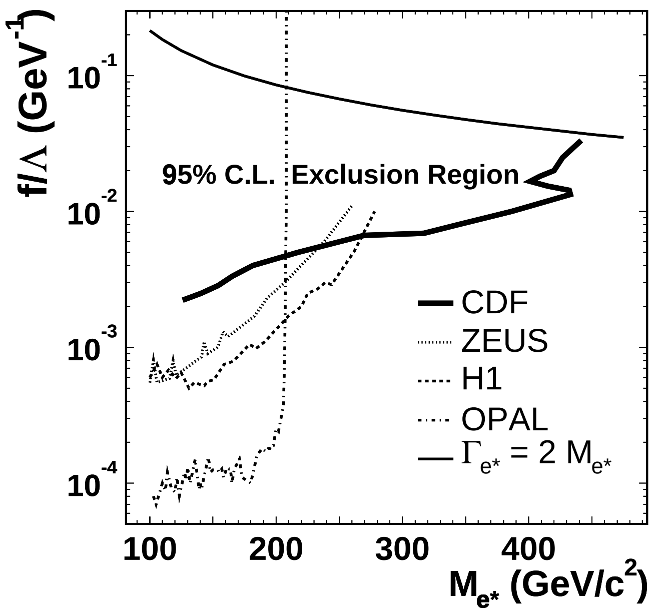

Fig. 13. Exclusion region at the 95% C.L. established by CDF for e^* production via a Gauge Mediated model.

(e^*) in association with an oppositely charged electron, where the e^* decays to an electron and a photon. Thus, the final state signature is two electrons and a photon where the search signal is a resonance in the electron+photon invariant mass spectrum.

Two models are studied: a Contact Interaction (CI) model[10] and a Gauge Mediated (GM) model[11]. The CI model depends on the mass of the e^* (M_{e^*}) and the composite energy scale (Λ). In the GM model, an excited electron is produced via the decay of SM γ^*/Z. This model depends on M_e^* and f/Λ, where f is a phenomonological coupling constant.

In the first search for excited leptons at a hadron collider, CDF found no excess of dielectron+photon events in 200 pb^{-1} of data. Exclusion regions for each model are established. Figure 12 shows the exclusion region at the 95% C.L. in the $M_{e^*}/\Lambda - M_{e^*}$ parameter space. There are no previously published limits for e^* production using the CI model. For the GM model, it is conventional to plot the 95% C.L. exclusion region in the $f/\Lambda - M_{e^*}$ parameter space, as shown in Figure 13. CDF extends the previously published limits from 280 GeV/c^2 to $\sim$ 430 GeV/c^2.

6 Summary

Searches for physics beyond the Standard model using 200 pb^{-1} to 450 pb^{-1} of data collected at CDF and DØ are presented. Currently, the experiments are actively persuing further exotic topics and analyzing up to the full 1 fb^{-1} of delevered luminosity. New and exciting results are coming out quickly. Further information regarding the analyses presented in this paper and new results can be found at[12] and[13].

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